A Comprehensive Overview of the Laser Based Calibration Facility at Measurement Standards Laboratory

Fazil Syed, Faheem Mohammad*, and Luai M. Al-Hadhrami

King Fahd University of Petroleum & Minerals,
P.O. Box # 496, KFUPM, Dhahran-31261, Kingdom of Saudi Arabia

King Fahd University of Petroleum & Minerals, Kingdom of Saudi Arabia

King Fahd University of Petroleum & Minerals, Kingdom of Saudi Arabia

**Corresponding author: mfaheem@kfupm.edu.sa*

Abstract

Non- destructive testing (NDT) describes a wide range of methods for measuring and comparing physical quantities against a nominal condition. The most familiar laser based optical non destructive methods are based on the interference of wave fronts of monochromatic light reflected from a test surface. This paper will focus primarily on the profound review of operating principles of laser based non destructive methods involved with the measurement principles at Measurement Standards Laboratory (MSL). Michelson Inteferometric Principles with emphasis on minimizing alignment errors for better results will be assessed. The paper also enlists the discussion about airy points and its impact on measurement results. Uncertainties associated with the measurement results have been estimated using the GUM: *Evaluation of measurement data — Guide to the expression of uncertainty in measurement* procedures. The Agilent 5530 Laser Calibration Facility does provide the much needed Flexibility and better control. The necessary compensation factors including wavelength, air and material compensation factors with their due influence on the repeatability of the measurement results are studied. The range of optics involved in the measurement process both in linear and angular measurement procedures will be evaluated. A summary overview of different errors like Cosine, Abbe, and Dead path Errors resulting from the measurement of laser based dimensional parameters will be discussed with profound insight. By virtue of the high quality of its calibration services, MSL has gained national and international recognition to the kingdom of Saudi Arabia. It provides expertise and state-of-the art measurement infrastructure to ensure that the accurate calibration results are achieved with high degree of reliability. Precision engineering measurements at MSL are traceable to national and international calibration laboratories such as National Institute of Standards and Technology (NIST), USA, Physikalisch Technische Bundesanstalt (PTB), Germany, National Physical Laboratory (NPL), UK, Commonwealth Scientific Industrial Research Organization (CSIRO), Australia and more.MSL operates under the Total Quality Management Scheme and in conformity with ISO/IEC-17025: *General requirements for the competence of testing and calibration laboratories* guidelines. The information presented in this paper is most useful to the metrological organizations, who want to get enriched with comprehensive and exhaustive study involving the laser based measurement systems. This research grade laser based non destructive system will improve the metrological capabilities and will be of greater importance to the industrial community at large in Saudi Arabia.

Keywords: Michelson's Interferometry, laser optics, airy points, laser alignment, uncertainty analysis

I. INTRODUCTION

The Measurement Standards Laboratory (MSL) is a primary level calibration and testing facility located within the Research Institute of the King Fahd University of Petroleum & Minerals (KFUPM) in Dhahran. MSL calibrates and tests scientific measuring instruments for the Research Institute, the University, for military, other government organizations and for private industry and commerce where appropriate. MSL is fully accredited by Saudi Arabian Standards Organization (SASO), which is a

National Measurement Lab (NML) of Saudi Arabia. It is also approved by the Saudi Arabian Oil Company (Saudi Aramco) and is a member of the US

National Conference of Standards Laboratories International (NCSL International). It operates under Total Quality Management (TQM) and in conformity with International Standards Organization (ISO) Standards 9000, 10012 and ISO/IEC 17025. The measurement standard devices used by MSL are referenced to actual physical principles or to a national laboratory such as National Institute of Standards and Technology (NIST) of U.S.A., National Physical Laboratory (NPL) of U.K., and Physikalisch Technische Bundesanstalt (PTB) of Germany, to insure compatibility with other high level calibration facilities. It has numerous calibration capabilities in electrical, radiation and mechanical areas. The calculation of measurement uncertainty is accomplished as per the guidelines for evaluating and expressing the uncertainty of measurement results [1, 2].

II. LITERATURE REVIEW

Bienas et al [3] have modified the commercial scanning force microscope (SFM) to improve its metrological performance and its calibration. For this purpose, a three-dimensional (3D) measuring system consisting of three miniature laser interferometers has been incorporated into the SFM measurements. The goal therefore was to calibrate the scales of movement axes, as well as cross-talk and Abbe errors, with respect to the entire measurement volume of the SFM. The effects can be significantly reduced by compensating for measured spatially dependent non-linearities, cross-talk and Abbe errors by modification of the SFM control software using regression functions. For characterizing the metrological performance, they have applied a model introduced in a three-coordinate measurement technique. Herewith, the spatially dependent performance is given by linear superposition of a set of one-dimensional functions. Further progress is achievable by logical reference to spatially distributed calibration points given by output signals of the laser interferometers. At the stage reached in the work at present, an expanded uncertainty $U = 5\ \text{nm} + 2\times10^{-4}\cdot l$ (where l = distance) is estimated for the distance measured between two points within a measured volume.

Farnum, Gregory T. [4] reviewed laser based metrology and inspection systems. This paper details their basic principles, and examines their strengths and weaknesses.

Pitt, D [5] reviewed new developments for the calibration of machine tools and co-ordinate measurement machines which were otherwise been lengthy processes. New developments, based on linear interferometry, and novel software methods have drastically reduced the time required for machine calibrations and installation acceptances. Stabilized HeNe laser systems for linear scales and calibration of machine tools, a novel porro-prism method of measuring straightness along a machine tool axis, a new system for lead screw error compensation, a Raman microscopy technique based on a He-Ne laser source to measure the homogeneity of diamond films grown by CVD and other techniques, were described.

Hans Jurgen [6] presented a metrological approach to the preparation, execution and evaluation (including expression of uncertainty) of measurements of translational and rotational motion quantities using laser interferometer methods and techniques. The realization and dissemination of the SI units of motion quantities (vibration and shock) have been based on laser interferometer methods specified in international documentary standards. New and upgraded ISO standards are reviewed with respect to their suitability for ensuring traceable vibration measurements and calibrations in an extended frequency range of 0.4 Hz to higher than 100 kHz. Using adequate vibration exciters to generate sufficient displacement or velocity amplitudes, the upper frequency limits of the laser interferometer methods specified in ISO 16063-11 for frequencies $\leq$ 10 kHz can be expanded to 100 kHz and beyond. A comparison of different methods simultaneously used for vibration measurements at 100 kHz will be demonstrated. A statistical analysis of numerous experimental results proves the highest accuracy achievable currently in vibration measurements by specific laser methods, techniques and procedures (i.e. measurement uncertainty 0.05 % at frequencies $\leq$ 10 kHz, $\leq$ 1 % up to 100 kHz).

Bahrawi, M. And Farid, Niveen [7] discussed the calibration method and the accompanying uncertainty budget. For precise length scale measurement, wavelengths of laser sources are often used as secondary definitions of the meter to serve in the measurement by dynamic interferometer. At their facility, an adapted technique is designed to calibrate graduation length with range up to 400 mm in terms of the wavelength of the He-Ne laser. The system comprises a motorized stage with single axis of motion, a microscope mounted on the driving carriage to detect the line position, mechanical mounts for the line scale, a digital camera coupled with the microscope and interfaced with a pc, displacement laser interferometer with data processing and recording unit, and sensors for recording environment parameters. The system uses two personal computers. One of them is connected to the controller and the stage. Its software controls the stage driving according to the operator instructions and allows automatic stage movement from zero position to the terminal during alignment procedure. It also governs moving the stage with steps correspond to the nominal scale graduation and positioning the scale line into the microscope view for detecting line centre. The other computer is connected with the displacement laser interferometer to determine the graduation length in terms of the compensated wavelength of the He-Ne laser. The adapted system uses static line detection mode which is the mostly used method in the laboratories, and on the other hand is more accurate than the dynamic detection mode. The calibration is affected by geometrical error, such as the straightness error associated with the deviations of the travelling stage movement from the main movement axis. Also the errors arise from the improper alignment of the system components. Both are compensated and analysed.

Penzes, W.B. et al [8] presented a novel technique for calibrating lines scales which uses electrical test structure metrology. Line scales are used throughout industry for a variety of applications. The most common is the stage micrometer, a small, graduated glass scale for the calibration of optical instruments such as microscopes. However, stage micrometers are generally not calibrated, except for critical applications, due to the time and cost of optical calibration techniques.

III. INTRODUCTION

The standard laser measurement system at MSL utilizes the principle of laser interferometry to obtain the length values. The material thermal expansion is compensated by measuring the temperature of the test item and referencing the length to 20°C. The system employs Michelson Interferometer [9] that produces interference by means of division of the amplitude of incident light by means of arrangements of mirrors and beam splitters. The basic elements of a Michelson interferometer are shown in the Figure 1.Light from the source *S* is incident at 45° on a half-silvered rear-surface M_3 of the beam splitter P_1 at point *A*. The transmitted ray *x* passes through the compensator P_2, reflects from the stationary mirror M_1 and returns through the compensator to point *A* where it reflects to the observer *O*. Meanwhile, the reflected ray *y* traverses P_1, reflects from movable mirror M_2, passes through P_1 and recombines with ray *x* as it goes to the observer *O*. The optical compensator P_2 ensures that both beams travel the same distance in glass.

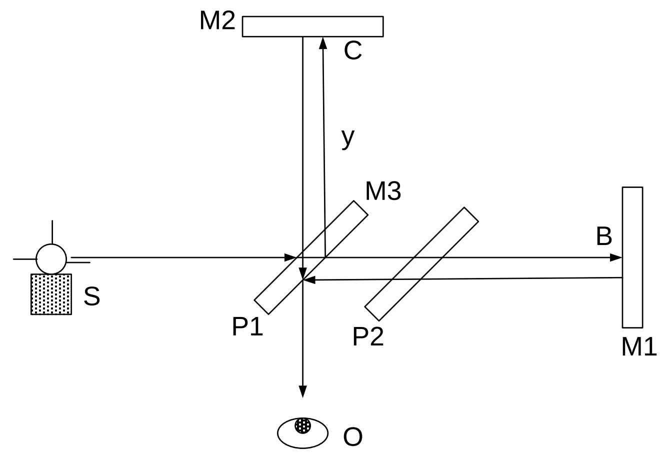

Figure 1: The Michelson Interferometer

Both rays then interfere at the observation point with a path difference *d* defined by the following equation

$$2\,d = 2\left|AB - AC\right|, \qquad (1)$$

Which results in a phase difference $\Delta\varphi_o$ given by

$$\Delta\phi_o = \vec{k}.\vec{r} = \frac{2\pi}{\lambda}\,2\,d\,, \qquad (2)$$

Where *k* is the wave vector of the light. Ray *x* undergoes two external reflections (at M_3 and M_1) whereas *y* undergoes only (at M_2) so an additional phase difference $\varphi_r = \pi$ is introduced for a total

$$\Delta\phi = \Delta\phi_o + \phi_r\,, \qquad (3)$$

$$= \frac{2\pi}{\lambda}\,2\,d \quad - \quad \pi\,, \qquad (4)$$

The condition for constructive interference is that the total phase difference $\Delta\varphi_o$ be an integral multiple of 2π, i.e.

$$2\,d = \left(m + \frac{1}{2}\right)\lambda\,, \qquad (5)$$

IV. IMPORTANT CONSIDERATIONS FOR LINEAR MEASUREMENTS

The following section summarizes the important considerations that are to be taken care while performing the length measurements using the interferometry principle.

Necessary Optics Involved for linear and angular measurements

Remote Interferometer, Retro reflectors, Reflector mount, Beam Bender,

Airy Points

These are used for precision measurement (metrology) to support a length standard in such a way as to minimize bending or droop. The points are symmetrically arranged around the centre of the length standard and are separated by a distance equal to

$$0.577 \times l \, , \qquad (6)$$

Where l (usually l > 150 mm) is the length of the specimen to be measured. Supporting the artifact at these points ensures that the calibrated length is preserved. If the length gauge is not supported at the Airy points, the measurement uncertainty is increased.

Wavelength Compensation

The speed of light changes as light travels through mediums of differing densities. The laser beam travels through air which has a density that varies with changes in temperature, pressure and humidity. This change in the speed of light changes the wavelength of the laser light which correspondingly changes the number of λ/4's counted along a given distance. This change can be corrected for by multiplying the number of λ/4's stored in the counters by the Compensation Factor. To correct the number of λ/4's, the compensation factor will always be less than one.

Material Temperature Compensation for Thermal Expansion

All the materials expand and contract with changes in temperature. This change in dimensions of each type of material differ as a function of temperature and can be measured which is termed as "thermal coefficient of expansion".

$$\alpha = \frac{\Delta l}{l \, \Delta t} \, , \qquad (7)$$

Where α is thermal coefficient of expansion, Δl is change in length and l is original length. The S.I unit of thermal coefficient of expansion is ppm/°C.

Cosine Error

It results from misalignment of the scale axis to the desired measurement axis. This results when the measurement axis and the scale axis are not parallel. It can be minimized with accurate alignments. The objective of an accurate alignment is to have the laser beam parallel to the axis of travel.

Abbe Error

The most overlooked problem in machine tools is Abbe error. It results from angular rotation between the scale axis and the measurement axis during a measurement and when there exists some distance between scale axis and measurement axis. The Abbe offset can be minimized by positioning the scale axis as close as possible to the measurement axis and maintaining angular components (Pitch, Yaw, and Roll) to minimum.

Dead path Error

Dead path is a segment of the laser measurement path between interferometer and the retroreflector that is not measured and stored in the Laser Display Counters. This results from resetting to zero with the optics separated by this dead path and then making a measurement. The unmeasured segment of the laser beam path cannot be compensated since it is not stored in the counters. Dead path errors are minimized when zero is established by positioning the interferometer and retroreflector as close as possible.

V. IMPORTANT CONSIDERATIONS FOR ANGULAR MEASUREMENTS

Accuracy

Accuracy of the angular optics is limited to four factors, namely, (a) approximation of the displayed value to arc seconds, (b) separation of the laser measurement paths, (c) Parallelism of the laser measurement paths and (d) thermal stability of the optics during a measurement.

Thermal Expansion

Measurement error can result from thermal expansion of a measuring instrument during a measurement. Thermal stability of the interferometer/beam bender and reflector mount can significantly affect measurement accuracy and precision.

Measurement Time Interval

Due to ambient conditions influencing the measurements, the time interval required for the measurement should be as short as possible. The angular optics gives optimal results when measurement times are short.

Flatness Measurement

The flatness of a surface such as a surface plate or a machine parts can be quickly determined with the angular optics and the calculator plotter option. HP Application Note 156-2 [10] explains briefly how the angular optics are used to collect the necessary data to calibrate a surface plate.

VI. CONCLUSIONS

This research grade laser based non destructive system will improve the metrological capabilities and will be of greater importance to the industrial community at large in Saudi Arabia.

VII. ACKNOWLEDGEMENT

The authors acknowledge the support provided by the Research Institute of King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia.

VIII. REFERENCES

[1] Barry N. Taylor and Chris E. Kuyatt, “Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results”, NIST Technical Note 1297, 1994.

[2] “Guidelines for evaluation and expression of uncertainty of measurement in calibration”, National Measurement & Calibration Lab, SASO, Saudi Arabia, 2006.

[3] Bienias, M., Gao, S., Hasche, K., Seeman, R., and Thiele, K., “3D calibration of a scanning force microscope with internal laser interferometers”, *Surface and Interface Analysis*, Vol. 25, No. 7-8, pp. 606-610, June-July 1997

[4] Farnum, Gregory T., “Measuring with Lasers”, *Manufacturing Engineering*, Vol. 96, No.2, pp 47-51, February 1986.

[5] Pitt, D. “Fast linear measurement and surface metrology techniques”, *Proceedings of SPIE- The International Society for Optical Engineering,* Vol. 1573, pp170-170, November 1991.

[6] Hans-Jurgen von Martens, “Metrology of vibration measurements by laser techniques”, *Eighth International Conference on Vibration Measurements by Laser Techniques, Italy*, June 2008.

[7] Bahrawi, M. And Farid, Niveen, “Adapted technique for length scale measurement”, *3rd International Metrology Conference, CAFMET 2010, Cairo,* pp228-232, April 2010.